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Growth-Simulation Model for Lodgepole Pine in Central Oregon

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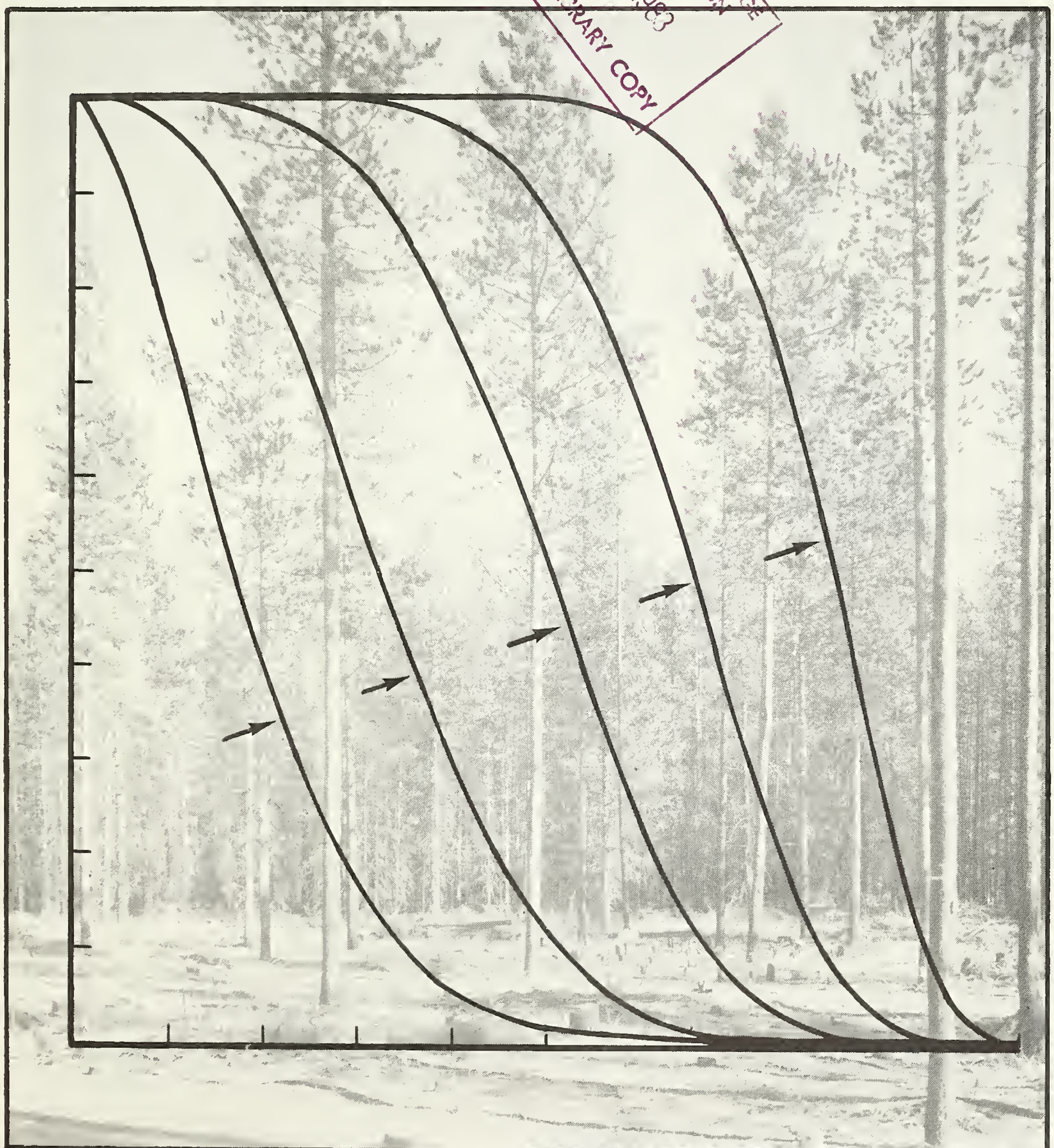

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Abstract

Dahms, Walter G. A growth simulation model for lodgepole pine in central Oregon. Res. Pap. PNW-302. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1983. 22 p.

A growth-simulation model for central Oregon lodgepole pine (*Pinus contorta* Dougl.) has been constructed by combining data from temporary and permanent sample plots. The model is similar to a conventional yield table with the added capacity for dealing with the stand-density variable. The simulator runs on a desk-top computer.

Keywords: Lodgepole pine (*Pinus contorta* Dougl.), yield table, variable stand density, growth simulation, gross increment, mortality, net increment, central Oregon.

Summary

The growth-simulation model for central Oregon lodgepole pine (*Pinus contorta* Dougl.) presented in this paper provides foresters with the capacity to "grow" lodgepole pine stands starting at different initial spacings and with different stand-density regimes.

The first step in growing trees is to estimate stand increment. Stand increment is apportioned to individual trees based on their height and diameter. Height is obtained from curves that estimate site index and height growth described in an earlier paper (Dahms 1975). Diameter is calculated from the updated height and volume by rearranging the volume equation and solving for diameter.

Mortality estimates are obtained from two levels-of-growing-stock studies in young stands, three plots in a Pringle Falls stand, and from a north Idaho stand studied by Hamilton and Edwards (1976).

Results are presented in terms of total cubic volume, merchantable cubic volume, and board-foot volume. Board-foot volume may be in terms of Scribner, or ¼-inch International. Merchantable tops of 5, 6, 7, or 8 inches may be selected with either log rule. Merchantable tops of 3, 4, or 5 inches may be chosen for merchantable cubic volume.

Three approaches to testing veracity of simulation outputs were tried:

1. Simulations were compared with actual growth results on three permanent sample plots over a 32-year period and from plots on two levels-of-growing-stock studies over a shorter period.
2. Gross and net yields were compared for sites ranging from the poorest to the best.
3. Simulated tree size was compared with actual tree-size distributions found on some temporary plots.

All of the comparisons indicated that simulations produced reasonable results. More comparisons over a longer period, like those in approach 1, would be desirable, but long-term records on permanent sample plots simply do not exist. The need for verification makes a strong case for continuing existing permanent sample plots.

The simulation model as presented is applicable to central Oregon lodgepole pine. The gross-volume-increment equation is based only on central Oregon data. The area of application could be broadened by gathering gross-volume-increment data from additional areas to determine if the existing equation fits, or to fit a new equation as the data might indicate.

Use of gross-cubic-volume increment as the main driving mechanism for the simulator with allocation of increment to individual trees, as has been done for lodgepole pine in this instance, would appear to have application for other species. This would seem to be especially true for a species such as ponderosa pine, where a considerable body of data from levels-of-growing-stock and spacing studies is available from a broad geographic area.

Contents

Introduction

Direct comparison of timber-management alternatives, such as varying rotation lengths or stand-density regimes, requires such long periods of time that comparisons of this kind are not practical. Historically, yield tables have been used to make them. The computer-simulation model presented in this paper differs from conventional yield tables only in that it has greater flexibility in dealing with the stand-density variable and therefore is a more flexible and useful form of yield table.

New stands that are replacing the old growth now being harvested provide foresters with real opportunities to concentrate more of the wood produced by lodgepole pine forests on trees that will reach usable size and to minimize losses from mountain pine beetle (*Dendroctonus ponderosae* Hopkins). Simulation provides an opportunity to see how the many combinations of initial spacing and subsequent stand-density regimes affect tree size, total production, and rotation length, thus providing the forest manager and economist with a basis for choosing the most desirable alternative.

Multiple use of forest land, such as for production of both wood and wildlife, increases the options of the land manager and makes the job of selecting the best alternative more difficult. Simulation of forest growth makes results of a particular choice clearer and opens the possibility of estimating production of such wildlife needs as food and cover from the simulated estimates of forest stand density.

Volume estimates are in terms of total cubic, merchantable cubic, and board feet. Several options for the kind of merchantable cubic and board-foot volumes are provided. Merchantable cubic is all volume above stump to a 3.0-, 4.0-, or 5.0-inch top as specified by the user. Board-foot volumes may be either Scribner, or International ¼-inch-kerf. Merchantable tops of 5.0, 6.0, 7.0, or 8.0 inches may be specified for either log rule.

The paper is divided into three main sections:

1. Running the simulator, using a Hewlett-Packard 9845A desk-top computer;[1]
2. How the simulator works; and
3. An appendix providing details to judge underlying equations and assumptions.

[1]The mention of products and companies by name does not constitute endorsement by the USDA, nor does it imply approval of a product to the exclusion of others that may be suitable.

Running the Simulation Program

The simulation model consists of a package of programs for a Hewlett-Packard 9845A desk-top computer. The basic sets start where heights and diameters of all trees have been measured or where heights have all been estimated from curves of height over diameter.

The set designed to start from permanent sample plots with all tree heights and diameters measured is called "LPSIM" and "LPSIM1" (lodgepole pine simulation). This pair of programs is essentially one, but was broken into two parts connected with a "LINK" statement to save storage space on the computer.

The second set is designed to start from prism-point data where diameters of all trees and height of the tallest tree have been measured. Heights of trees where diameter only was measured are estimated from curves of height over diameter. This set of programs is called "LPPRI" (lodgepole pine prism) and "LPPRI1." They also are essentially one, but broken into two pieces connected with a "LINK" statement.

Differences between these two sets of programs arise because the height and diameter data are stored on tape differently.

Several support programs are also included in the simulation package:

1. "STORE" is used to enter diameter and height of each tree for storage on tape for entry into the "LPSIM" programs. To use this program, put the tape into the T15 slot and load "STORE." List the program to obtain further instructions.
2. "STORPR" is designed to convert diameters of trees and height of the tallest one at a prism point into height and diameter of each tree expanded to a 1/5-acre basis. Heights consist of regression-estimated heights plus or minus a random-error term. To use this program, load it into memory and list it for further instructions.
3. "SINDEX" is used to calculate a density-corrected site index from total height and breast-high age of a single tallest tree. Load this program into memory and list it to obtain instructions for using the program and measurements required.
4. "CCF" is designed to give a stand-density estimate in terms of crown competition factor (C.C.F.) from tree-diameter measurements at a prism point. To use the program, load it into computer memory and list it for instructions.
5. "INSTR" provides instructions for running the "LPSIM" programs. The instructions are obtained by loading "INSTR" into memory and listing it.
6. "INSTR1" provides instructions for running the "LPPRI" programs. To obtain the instructions, load "INSTR1" into computer memory and list it. Support programs appropriate for use with the "LPSIM" programs are stored on the tape with "LPSIM," and programs to be used with program "LPPRI" are stored with "LPPRI."

Summary tables give a great deal of information about the simulated stand (exhibit 1). Basal area, volume, number of trees, and average tree height by 2-inch diameter classes are given for the final year of the simulated stand. Other tables give live-stand values at 5-year intervals, trees that died by 5-year periods, trees cut in thinning, and increment and financial aspects of the stand at 5-year intervals. Site index, interest rate, time to which stumpage value is discounted, stumpage value, time of thinnings, and percent of stems to be cut are shown at the bottom of the summary tables.

Exhibit 2 shows tables produced if a complete printout is called for. These tables show basal area, volume, number of trees, and average height by 2-inch diameter classes. This information is needed to determine how many trees to cut and what volumes may be available by tree size for any possible thinning.

Grand summary tables, similar to those shown as exhibit 1, are also produced where more than one plot or more than one random start per plot is requested. These tables represent averages for a number of simulation runs.

The programs that make up the lodgepole pine growth-simulation model will run as written on the Hewlett-Packard 9845A desk-top computer. These programs can also be run on a Hewlett-Packard 9845B with only slight modification. Potential Forest Service users of these programs can obtain copies of these tapes from the Regional Office in Portland. Others can obtain copies from the Silviculture Laboratory in Bend.

Anyone wishing to adapt these programs for use on other computers may obtain a listing from the Silviculture Laboratory. The programs are written in BASIC, which is similar to FORTRAN.

EXHIBIT 1

JANUARY 8,1983
BEATTY CREEK SPACING STUDY,15X15 FEET,PLOT 9
SCRIBNER BD. FT. VOL. ALL TREES 7.6 INCHES D.B.H. & UP TO A 5 INCH TOP
MERCHANTABLE CUBIC VOL. ALL TREES 4.6 INCHES D.B.H. & UP TO A 3 INCH TOP
MANAGED STAND MORTALITY
ALL VALUES PER ACRE BASIS

PROJECTED BASAL AREA AND VOLUME BY TREE SIZES AGE 64

	BASAL AREA	VOLUME CUBIC TOTAL	VOLUME CUBIC MERCH.	VOLUME BD.FT.	NUMBER TREES	AVERAGE HEIGHT
TREES LESS THAN 4.6 INCHES	0.0	0			0	0
TREES 4.6 TO 6.5	0.0	0	0		0	0
TREES 6.6 TO 8.5	0.0	0	0	0	0	0
TREES 8.6 TO 10.5	0.0	0	0	0	0	0
TREES 10.6 TO 12.5	3.1	67	64	226	4	53
TREES 12.6 TO 14.5	16.2	363	350	1395	16	55
TREES 14.6 TO 16.5	33.3	786	766	3344	26	59
TREES LARGER THAN 16.5	43.5	1088	1069	5178	24	64
TOTALS OR AVERAGE	96.1	2303	2249	10143	69	60

SUMMARY TABLES

LIVE STAND STATISTICS

AGE	NO. TREES	BASAL AREA	CCF	AVG. DIA.	AVG. HT.	CUBIC VOLUME TOTAL	CUBIC VOLUME MERCH.	BD.FT. VOLUME
19	192	22.9	34	4.6	18.6	248	180	0
19	75	11.6	16	5.3	20.6	129	123	0
24	75	24.7	27	7.7	24.3	303	286	208
29	75	36.1	37	9.3	29.3	496	464	890
34	73	46.4	45	10.7	34.4	711	669	1770
39	73	57.0	54	11.9	39.2	962	912	2894
44	73	66.8	61	12.9	43.9	1231	1178	4205
49	73	76.0	68	13.7	48.3	1514	1459	5662
54	73	84.6	75	14.4	52.3	1807	1752	7230
59	73	92.8	81	15.1	56.1	2107	2051	8879
64	69	96.1	83	15.8	59.7	2303	2249	10143

PERIODIC MORTALITY

PERIOD AGES INCLUSIVE	NO. TREES	BASAL AREA	AVG. DIA.	AVG. HT.	CUBIC VOLUME TOTAL	CUBIC VOLUME MERCH.	BD.FT. VOLUME
20 THRU 24	0	0.0	0.0	0.0	0	0	0
25 THRU 29	0	0.0	0.0	0.0	0	0	0
30 THRU 34	2	.8	8.5	26.1	10	9	12
35 THRU 39	0	0.0	0.0	0.0	0	0	0
40 THRU 44	0	0.0	0.0	0.0	0	0	0
45 THRU 49	0	0.0	0.0	0.0	0	0	0
50 THRU 54	0	0.0	0.0	0.0	0	0	0
55 THRU 59	0	0.0	0.0	0.0	0	0	0
60 THRU 64	4	4.6	14.5	56.0	103	100	416
TOTALS	6	5.3			113	109	428

TREES CUT IN THINNING

AGE	NUMBER TREES	BASAL AREA	AVG. DIA.	AVG. HT.	CUBIC VOLUME TOTAL	CUBIC VOLUME MERCH.	BD. FT. VOLUME	DISCOUNTED VALUE
19	117	11.3	4.1	17.4	118	57	0	$ 0.00
TOTALS	117	11.3			118	57	0	$ 0.00

INCREMENT AND FINANCIAL ASPECTS

AGE	MEAN ANN. INCREMENT CUBIC**	MEAN ANN. INCREMENT BD. FT.	DISCOUNTED VALUES	GROWTH PERCENT * TOTAL CU.	GROWTH PERCENT * BD.FT.
19	13.0	0	$ 0.00	0.0	0.0
19	6.8	0	$ 0.00	0.0	0.0
24	12.6	9	$ 13.48	16.1	0.0
29	17.1	31	$ 49.68	9.6	24.8
34	20.9	52	$ 85.23	7.1	13.2
39	24.7	74	$ 120.18	6.0	9.6
44	28.0	96	$ 150.63	4.9	7.4
49	30.9	116	$ 174.96	4.1	5.9
54	33.5	134	$ 192.70	3.5	4.9
59	35.7	150	$ 204.15	3.1	4.1
64	36.0	158	$ 201.17	1.8	2.7

* GROWTH PERCENT AT MIDDLE OF THE 5-YEAR PERIOD ENDING AT AGE SHOWN
** MEAN ANNUAL INCREMENT IS FOR TOTAL CUBIC VOLUME INCREMENT

SITE INDEX= 90
AGE SIMULATION STOPPED= 64
INTEREST RATE= 3 PERCENT
DISCOUNTED VALUE CALCULATED TO AGE SIMULATION STARTED
STUMPAGE VALUE CALCULATED AT 75 DOLLARS PER M
CUT 60 PERCENT OF TREES IN PRECOMMERCIAL THINNING
DONE

EXHIBIT 2

OCTOBER 5,1982
BEATTY CREEK STUDY,15X15 FOOT SPACING,PLOT 1
SCRIBNER BD. FT. VOL. ALL TREES 7.6 INCHES D.B.H. & UP TO A 5 INCH TOP
MERCHANTABLE CUBIC VOL. ALL TREES 5.6 INCHES D.B.H. & UP TO A 3 INCH TOP
MANAGED STAND MORTALITY
ALL VALUES PER ACRE BASIS

PROJECTED BASAL AREA AND VOLUME BY TREE SIZES AGE 19

	BASAL AREA	VOLUME CUBIC TOTAL	VOLUME CUBIC MERCH.	VOLUME BD.FT.	NUMBER TREES	AVERAGE HEIGHT
TREES LESS THAN 4.6 INCHES	10.4	108			117	17
TREES 4.6 TO 6.5	10.6	116	8		75	20
TREES 6.6 TO 8.5	0.0	0	0	0	0	0
TREES 8.6 TO 10.5	0.0	0	0	0	0	0
TREES 10.6 TO 12.5	0.0	0	0	0	0	0
TREES 12.6 TO 14.5	0.0	0	0	0	0	0
TREES 14.6 TO 16.5	0.0	0	0	0	0	0
TREES LARGER THAN 16.5	0.0	0	0	0	0	0
TOTALS OR AVERAGE	21.0	224	8	0	192	18

TREES CUT AT AGE 19

	BASAL AREA	VOLUME CUBIC TOTAL	VOLUME CUBIC MERCH.	VOLUME BD.FT.	NUMBER TREES	AVERAGE HEIGHT
TREES LESS THAN 4.6 INCHES	9.2	95			105	17
TREES 4.6 TO 6.5	1.5	16	0		12	19
TREES 6.6 TO 8.5	0.0	0	0	0	0	0
TREES 8.6 TO 10.5	0.0	0	0	0	0	0
TREES 10.6 TO 12.5	0.0	0	0	0	0	0
TREES 12.6 TO 14.5	0.0	0	0	0	0	0
TREES 14.6 TO 16.5	0.0	0	0	0	0	0
TREES LARGER THAN 16.5	0.0	0	0	0	0	0
TOTALS OR AVERAGE	10.6	111	0	0	117	18

PROJECTED BASAL AREA AND VOLUME BY TREE SIZES AGE 19

	BASAL AREA	VOLUME CUBIC TOTAL	VOLUME CUBIC MERCH.	VOLUME BD.FT.	NUMBER TREES	AVERAGE HEIGHT
TREES LESS THAN 4.6 INCHES	1.3	13			12	18
TREES 4.6 TO 6.5	9.1	100	8		63	20
TREES 6.6 TO 8.5	0.0	0	0	0	0	0
TREES 8.6 TO 10.5	0.0	0	0	0	0	0
TREES 10.6 TO 12.5	0.0	0	0	0	0	0
TREES 12.6 TO 14.5	0.0	0	0	0	0	0
TREES 14.6 TO 16.5	0.0	0	0	0	0	0
TREES LARGER THAN 16.5	0.0	0	0	0	0	0
TOTALS OR AVERAGE	10.3	113	8	0	75	20

PROJECTED MORTALITY AGE 20 THROUGH 24 INCLUSIVE

	BASAL AREA	VOLUME CUBIC TOTAL	VOLUME CUBIC MERCH.	VOLUME BD.FT.	NUMBER TREES	AVERAGE HEIGHT
TREES LESS THAN 4.6 INCHES	0.0	0			0	0
TREES 4.6 TO 6.5	0.0	0	0		0	0
TREES 6.6 TO 8.5	0.0	0	0	0	0	0
TREES 8.6 TO 10.5	0.0	0	0	0	0	0
TREES 10.6 TO 12.5	0.0	0	0	0	0	0
TREES 12.6 TO 14.5	0.0	0	0	0	0	0
TREES 14.6 TO 16.5	0.0	0	0	0	0	0
TREES LARGER THAN 16.5	0.0	0	0	0	0	0
TOTALS OR AVERAGE	0.0	0	0	0	0	0

PROJECTED BASAL AREA AND VOLUME BY TREE SIZES AGE 24

	BASAL AREA	VOLUME CUBIC TOTAL	VOLUME CUBIC MERCH.	VOLUME BD.FT.	NUMBER TREES	AVERAGE HEIGHT
TREES LESS THAN 4.6 INCHES	0.0	0			0	0
TREES 4.6 TO 6.5	2.4	27	26		12	20
TREES 6.6 TO 8.5	18.7	227	215	117	59	24
TREES 8.6 TO 10.5	1.8	23	21	34	4	27
TREES 10.6 TO 12.5	0.0	0	0	0	0	0
TREES 12.6 TO 14.5	0.0	0	0	0	0	0
TREES 14.6 TO 16.5	0.0	0	0	0	0	0
TREES LARGER THAN 16.5	0.0	0	0	0	0	0
TOTALS OR AVERAGE	22.9	277	262	151	75	23

How the Simulator Works

Volume and Tree-Size Projection

Volumes are projected from estimates of gross cubic-volume increment for the stand. Height growth is obtained from curves that estimate site index and height growth described in an earlier paper (Dahms 1975). Stand increment is apportioned to an individual tree based on diameter and height of that tree relative to diameter and height of all trees on the plot. Diameter is calculated from the updated volume and height of the tree. Growth of each tree is simulated in this way a year at a time.

The equation for gross-volume increment was obtained from natural stands as described in earlier papers (Dahms 1964, 1975). The relation of volume increment in the managed stand to stand density was obtained from two levels-of-growing-stock studies and an initial spacing study.

The user has the option of using the volume increment in the natural stand or of increasing or decreasing it by a percentage if the particular use indicates a higher or lower growth rate is probable.

Thinning

The type of thinning built into the model has the small, weak, or diseased trees cut. The user specifies intensity of thinning as a percent of stems to be removed. Because a random element exists in selection of trees to be cut, percent specified is not always exactly achieved.

Flexibility in the kind of thinning desired can be achieved by combining a lower size limit with percent of trees to be cut. Even though the percent-of-cut equation will select small trees for cutting, an "If screen" returns trees below the specified size to the reserve stand.

Mortality

Five mortality options are available:

1. No mortality;
2. Managed-stand mortality;
3. Pringle Falls mortality;
4. North Idaho natural-stand mortality; or
5. Combined mortality.

The managed-stand mortality is based on a 15-year record for two central Oregon levels-of-growing-stock studies. Because thinning occurred at 5- to 10-year intervals, it represents losses at a fairly high intensity of management.

Pringle Falls mortality represents 32 years of records on three 1/2-acre plots — two thinned and one unthinned — in a stand that was heavily attacked by rust cankers. Mortality was heavy and mostly attributable to rust cankers caused by *Peridermium harknessii* J.P. Moor and *P. stalactiforme* Arth. and Kern. Deaths were spread fairly uniformly over the years of record.

The natural-stand mortality from north Idaho was taken from Hamilton and Edwards (1976). Combined mortality uses managed-stand mortality through age 59 and then goes to natural-stand mortality. The assumption is that older stands will suffer more mortality.

The mortality options presented leave much to be desired because possible management alternatives for reducing tree losses cannot be evaluated. For example, what effect will frequency of thinning have on number of trees lost between thinnings? Is mortality related to age or stand density? These are important questions when we think about desirable density regimes and culmination of mean annual increment. Despite the shortcomings of the present mortality estimates, they are a start in the right direction and give foresters some idea of the range of mortality and of the kind of data needed to improve estimates.

None of the mortality estimates makes allowance for catastrophic losses, such as might occur from a major attack of mountain pine beetles. Recent information linking stand density to the susceptibility of lodgepole pine trees to mountain pine beetle attack (Mitchell et al. in press) means that by proper stand-density control, catastrophic outbreaks might be averted.

Measuring Stand Density

Crown competition factor[2/] (C.C.F.) was chosen as the measure of stand density to be used with this lodgepole pine simulation model because a given C.C.F. comes close to representing a constant tree competition regardless of stand age, tree size, or site quality. The relation of C.C.F. to basal area shown in table 1 indicates that for a given C.C.F., basal area starts out small with small trees and rises rapidly with increasing tree size. As tree size increases, the rate of basal area increase slows.

A useful fact for those accustomed to thinking in terms of basal area is that for 10-inch trees, C.C.F. and basal area are so nearly the same that thinking of them as identical does not introduce a significant error (table 1).

C.C.F. compares growing space available to a tree with that represented by a vertical projection of the crown of the average open-grown tree of the same d.b.h. A C.C.F. of 100 means individual trees have, on the average, as much growing space as that represented by the crown of an open-grown tree. A C.C.F. of 200 means half as much space per tree as the open-grown tree-crown area, and a C.C.F. of 50 means twice as much.

[2/] Crown-competition factor is more fully described by Krajicek and others (1961).

Table 1 — Basal area and number of trees per acre by size class for crown-competition factor (C.C.F.) values 60, 100, and 140

Diameter	Basal area C.C.F. 60	Basal area C.C.F. 100	Basal area C.C.F. 140	Trees C.C.F. 60	Trees C.C.F. 100	Trees C.C.F. 140
Inches		*Square feet*			*Number*	
2	19.5	32.5	45.4	893	1,488	2,083
4	36.4	60.6	84.8	417	694	972
6	47.1	78.7	110.1	240	401	561
8	54.5	90.8	127.4	156	260	365
10	60.0	99.8	139.6	110	183	256
12	63.6	106.0	148.4	81	135	189
14	66.3	111.2	156.1	62	104	146
16	69.8	115.9	162.0	50	83	116

Testing the Simulation Model

The simulation model was tested three ways:

1. Comparing actual and simulated performance on three plots from age 55 to 87 years and from plots on two levels-of-growing-stock studies over a shorter period.
2. Comparing gross and net yields for lodgepole pine and a comparison of this relation with that for ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco).
3. Comparing size distribution, average diameter, and total cubic volume between simulation estimates and actual plot values in some older stands.

The first comparison tested all aspects of the simulation model. Three plots is a small number, however, and 32 years is a short time for a comparison. Consequently, other ways to test the model were sought.

The gross-volume-increment equation can be tested by comparing gross yield, a cumulative total of gross increment, with net yield. Similar comparisons are available for ponderosa pine and Douglas-fir to form a basis for judging the comparison for lodgepole pine.

A third kind of test, aimed at comparing diameter distribution of simulated stands with actual ones, tests the volume-increment distribution to individual trees and, indirectly, height growth.

All three kinds of tests indicate the simulation model is producing estimates close to actual stand performance. Actual comparisons are covered in much greater detail in the Appendix.

Literature Cited

Assman, Ernest. The principles of forest yield study. Gardiner, Sabine H., transl. Oxford, NY: Pergamon Press; **1970.** 506 p.

Bruce, David; DeMars, Donald J. Volume equations for second growth Douglas-fir. Res. Note PNW-239. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1974.** 5 p.

Dahms, Walter G. Correction for a possible bias in developing site index curves from sectioned tree data. J. For. 61(1): 25-27; **1963.**

Dahms, Walter G. Gross and net yield tables for lodgepole pine. Res. Pap. PNW-8. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1964.** 14 p.

Dahms, Walter G. Fifty-five year old lodgepole pine responds to thinning. Res. Note PNW-141. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1971a.** 13 p.

Dahms, Walter G. Growth and soil moisture in thinned lodgepole pine. Res. Pap. PNW-127. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1971b.** 32 p.

Dahms, Walter G. Tree growth and water use response to thinning in a 47-year-old lodgepole pine stand. Res. Note PNW-194. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1973**. 14 p.

Dahms, Walter G. Gross yield of central Oregon lodgepole pine. In: Baumgartner, David M., ed. Management of lodgepole pine ecosystems: Proceedings of a symposium. Pullman, WA: Washington State University; **1975:** 208-232.

Hamilton, David A. Event probabilities estimated by regression. Res. Pap. INT-152. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; **1974.** 18 p.

Hamilton, David A., Jr.; Edwards, Bruce M. Modeling the probability of individual tree mortality. Res. Pap. INT-185. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; **1976.** 22 p.

Krajicek, John E.; Brinkman, Kenneth A.; Gingrich, Samuel F. Crown competition — a measure of stand density. For. Sci. 7: 35-42; **1961.**

Meyer, Walter H. Yield of even-aged stands of ponderosa pine. Tech. Bull. 630. Washington, DC: U.S. Department of Agriculture; **1938.** 59 p.

Mitchell, R.G.; Waring, R.H.; Pitman, G.P. Thinning lodgepole pine in Oregon to increase tree vigor and reduce mountain pine beetle attack. For. Sci. [In press].

Staebler, George R. Gross yield and mortality tables for fully stocked stands of Douglas-fir. Res. Pap. PNW-14. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1955.** 14 p.

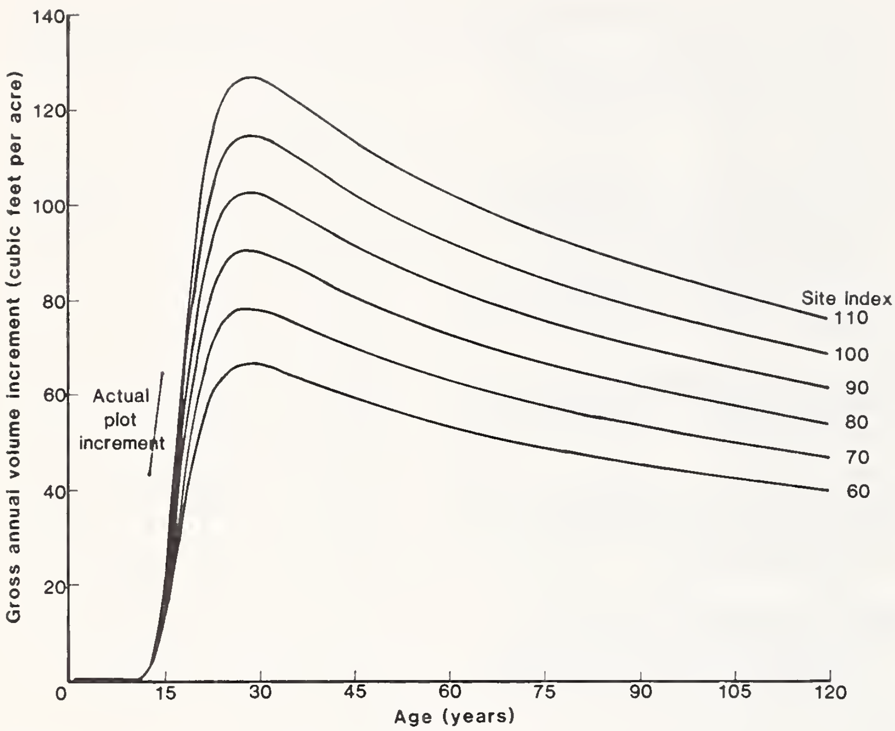

Figure 1. — Gross-increment equation before adjusting the extrapolated portion between age 0 and 25 years. Values presented are for the average density found on the gross-yield plots.

Appendix

The Gross-Increment Equation

The gross-increment equation is one of the basic parts of the lodgepole pine simulation model. It was fit to gross-increment data from 94 temporary plots established in natural stands on the eastern slope of the Cascade Range, between Crater Lake National Park in the south and Bend in the north. The relation of stand density to volume increment was derived from data obtained from two levels-of-growing-stock studies and a spacing study.

The equation for gross-volume increment has evolved over the years. The first equation,

Annual cubic volume increment per acre = 1.42 - .0439 (C.C.F.) + .01109 (C.C.F. × site index) - .003366 (site index × age),

was part of the gross and net yield tables for lodgepole pine (Dahms 1964). The second,

Log_e volume increment = 8.77295 - 1.5877 × (Log_e C.C.F.) + 1.07996 × (Log_e site index) - 3.32686 × (Log_e age) + .599002 × (Log_e age × Log_e C.C.F.),

where C.C.F. = 176.3 - .2407 × age, was part of a general assembly of information on lodgepole pine (Dahms 1975). Both of these equations covered the age range of the data from 25 to 120 years and relied on the relation of volume increment to stand density found in natural stands.

The latest version of the equation has been extrapolated to include the age range from 0 to 25 years. The first attempt is shown as figure 1. This equation is of the form

Log_e volume increment = A + B × (1 - $e^{-K \times \text{age}}$) - K × Log age;

where A is a function of site index and B is a function of both C.C.F. (stand density) and site index.

The extrapolated portion of the equation is definitely bounded by almost zero at the time the stand reaches breast height and known values at age 25 years. Two tests were applied to check reasonableness of the extrapolated portion of the equation:

1. A cumulative summary of increment from the gross-increment equation should exceed net yield to age 25 years.
2. Increment from two plots with trees spaced at 6 × 6 feet[3] was available for comparison.

A comparison of increment on the two permanent sample plots as shown in figure 1 indicates increment started faster on the plots than the extrapolated equation shows. Similarly, the comparison of a cumulative summary of increment from the gross-increment equation with net yield to age 25 showed net yield to be greater. Clearly, the extrapolated growth rate needed to be increased.

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[3] The Beatty Creek spacing study was installed in a dense stand of lodgepole pine seedlings, mostly 4 years old, that came in after the 1960 Anthony Lakes burn. Elevation is about 5,800 feet and site index about 90 feet. Soil is a tolo silt loam with 1 to 2 feet of ash overlying a silt loam to clay loam buried soil. Spacings represented were 6 × 6 feet, 9 × 9, 12 × 12, 15 × 15, and 18 × 18. Excess trees were pulled up by hand. Only an occasional tree had to be transplanted to achieve the desired spacing. Increment figures for the two 6 × 6-feet plots were for midperiod ages 12.5 and 14.5 years.

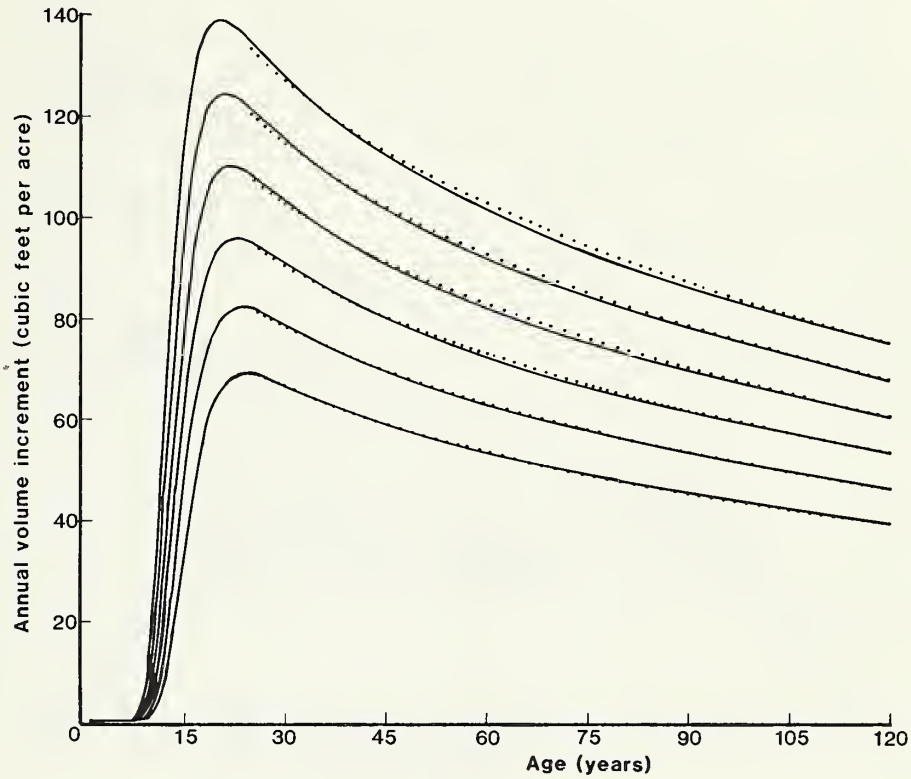


Figure 2. — A comparison of an earlier linear logarithmic volume-increment equation (dotted) with the present equation including the extrapolated portion (solid).

To increase the early growth rate indicated by the equation,

Log volume increment = A + B × (1 - e $^{-K \times age}$) - K Log age,

the coefficient K was split into two coefficients to give an equation of the form

Log_e volume increment = A + B × (1 - e $^{-K1 \times age}$) - K × Log age.

The coefficient K1 was adjusted to produce the result shown as figure 2. This equation does match the growth in permanent sample plots quite well, and also the cumulative-increment summary compares well with net yield, as will be shown later. As more data become available from Beatty Creek and other spacing studies, the equation can be improved.

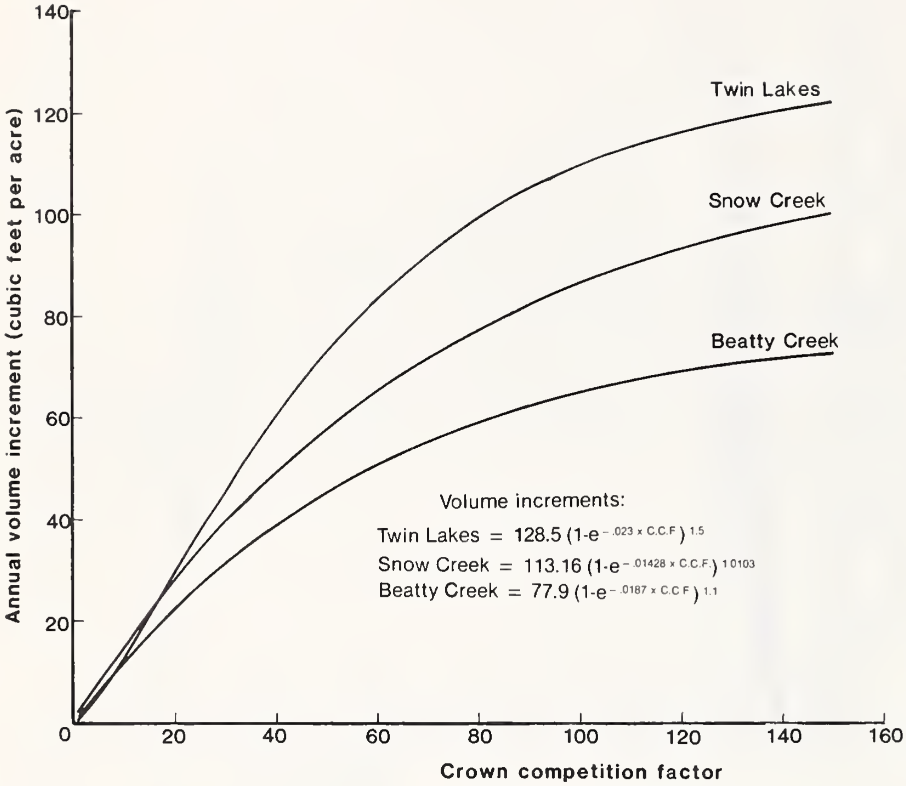
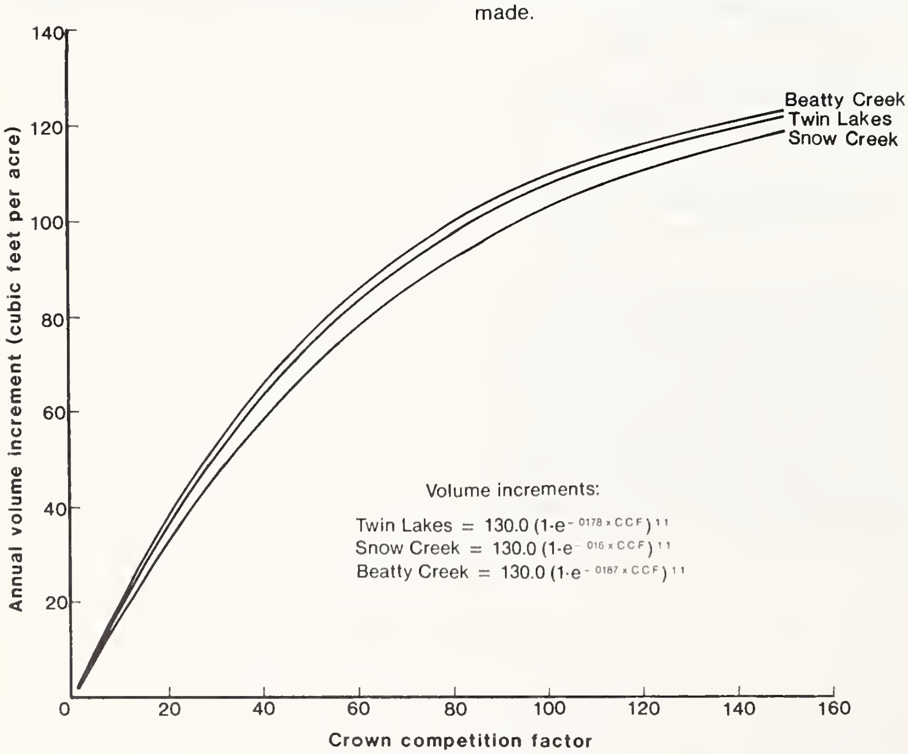


Figure 3. — Comparison of volume increment over stand density (C.C.F.) curves at Twin Lakes, Snow Creek, and Beatty Creek before any adjustments were made.



Introducing the Relation of Stand Density to Volume Increment

Introducing the relation of average stand density to volume increment that was found on two levels-of-growing-stock studies and a spacing study was the final step in fitting the gross-increment equation. This relationship from the two studies was more desirable than that found in the natural stands sampled by the gross-increment plots because:

1. The levels-of-growing-stock study estimate seemed a much better estimate of managed-stand performance.[4]
2. The levels-of-growing-stock and spacing studies had plots at very low densities, as well as higher ones. The natural stand plots did not cover the low-density end of the range.

Data from the two levels-of-growing-stock studies and one spacing study were available. The Twin Lakes study (described more fully in Dahms 1971b) is in a young stand that averaged 35 years old during the latest growth period and is growing on a very good site. The Snow Creek study (see Dahms 1973) averaged 59 years of age during the latest growth period and is growing on a medium site. Both of these studies are located on pumice soil in central Oregon. Trees of the Beatty Creek spacing study (see footnote 3) averaged 14.5 years during the latest growth period and are growing on a near-average site in the Blue Mountains.

[4] Stand density and site quality almost inevitably become confounded where widely scattered single plots are used, so that site index is the only measure of site quality. In the levels-of-growing-stock studies, site quality is held essentially constant with only stand density varying. Small, unintentional variations in site quality show up as slightly increased variation.

Figure 4. — Volume increment as a function of stand density (C.C.F.) at Beatty Creek, Twin Lakes, and Snow Creek with common N1 and B values to compare shape of curves.

The curves of volume increment over stand density for the latest growth period available at the Twin Lakes and Snow Creek levels-of-growing-stock studies, and the Beatty Creek spacing study, as shown in figure 3, have generally similar shapes. Equations for the three studies are:

Beatty Creek spacing

Volume increment
$= 77.9\,(1 - e^{-.0187 \times C.C.F.})^{1.1}$.

Twin Lakes levels-of-growing-stock

Volume increment
$= 128.5\,(1 - e^{-.023 \times C.C.F.})^{1.5}$.

Snow Creek levels-of-growing-stock

Volume increment
$= 113.2\,(1 - e^{-.01428 \times C.C.F.})^{1.0103}$.

These equations are all of the form

Volume increment
$= B\,(1 - e^{-K \times C.C.F.})^{N}$.

The coefficient B controls the ultimate height of the curve and is therefore related to site quality and stand age. The coefficients K and N control the shape of the curves.

The shape of these curves can best be compared if B, or the ultimate height, is held constant as in figure 4. The shapes are quite similar except the Twin Lakes one has a peculiar shape at the very low end, where adding more density causes volume increment to climb more slowly there than for the other two studies. This peculiarity seems hard to explain in biological terms and is therefore treated as a peculiarity of the data.

To make the curves more nearly the same shape and to see if any trends occur with age, an average N coefficient of 1.1 was used, and new equations, as shown in figure 5, were calculated. This change produced a more biologically logical shape for the Twin Lakes curve. It also brought out a gradual flattening of the curve, or slowing of the rise in volume increment with increasing stand density with greater age. Final curves of volume increment over stand density for each study are shown as figure 5.

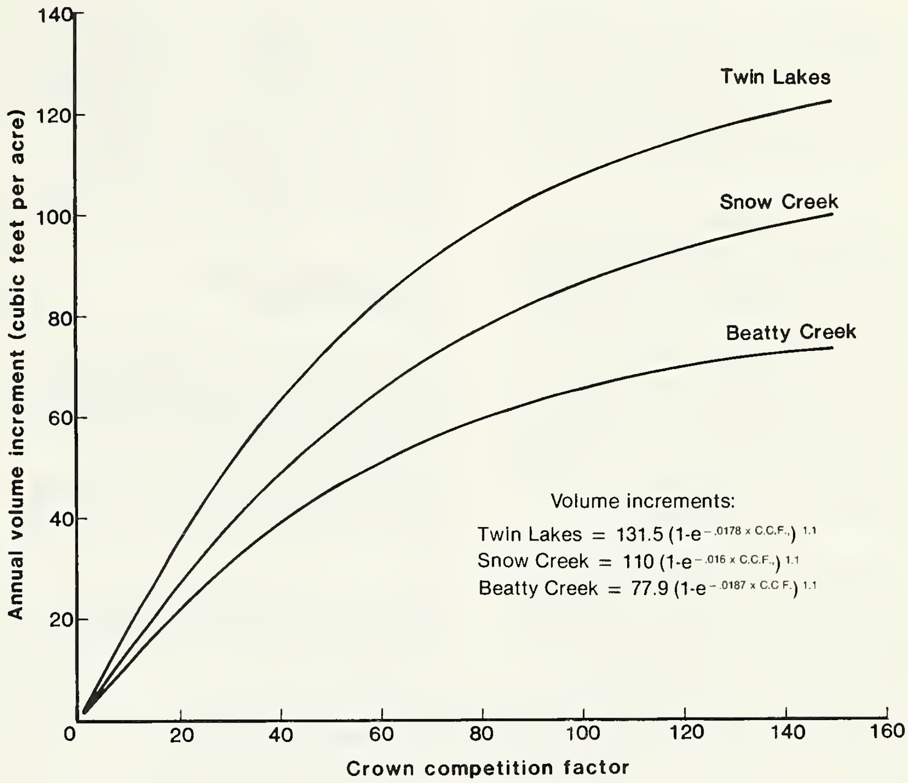


Figure 5. — Volume increment as a function of stand density (C.C.F.) at Twin Lakes, Snow Creek, and Beatty Creek.

Restricting the N value to 1.1 for all curves reduced percent of variation accounted for by stand density at Twin Lakes from .8658 to .8607 and left the percentages unchanged at .9291 at Snow Creek and .9822 at Beatty Creek, an almost insignificant loss of fit.

To accept the flattening trend of the curves with increasing age solely on the basis of the present three studies might be considered unwarranted. A similar trend showed up in the linear logarithmic equation that was fit to the natural-stand gross yield plots, however, and Assman (1970) describes such a change with age in the shape of curves of volume increment over stand density in German studies. Therefore, the trend was accepted as real.

The relation of volume increment to stand density shown by the levels-of-growing-stock and spacing studies does not get into the high-density area where volume increment begins to decline with increasing density. Ideally, this part of the density range should be covered, but lack of these kinds of data should not be critical in estimating results of possible manipulations of managed stands. Those who operate the simulator should not go much beyond C.C.F. 200.

The final gross-increment equation together with a linear logarithmic equation fit to the gross-yield plot data are shown as figure 2. Note the very close resemblance of the two equations from age 25 on. The relation of volume increment to stand density taken from the levels-of-growing-stock and spacing studies was fitted into the gross-increment equation so that volume increment was the same for managed stands and natural stands at the average-stand density for natural stands represented by the equation

$$\text{C.C.F.} = 176.3 - .2407 \times \text{age}.$$

The equations of figures 1 and 2 both represent the relation of volume increment to age at the average stand density found on plots in the natural stands. Although none of the plots were thinned, if one stand were to follow the stand-density regime specified, a thinning would have to be made every year.

Estimating Growth of Individual Trees

Individual tree-growth estimates are obtained each year by allocating a portion of total plot increment to each tree, getting an updated height from the height-growth or site-index estimating curves, and then with height and volume known, solving the volume equation for diameter.

Stand or plot-volume increment is allocated to individual trees on the basis of the proportion

$$\frac{\text{Tree volume increment}}{\text{Plot volume increment}} = \frac{\text{Tree } D^{1.818} \times H^{1.786}}{\Sigma(\text{Tree } D^{1.818} \times H^{1.786})}$$

The particular power of diameter and height were derived from permanent sample-plot data, where diameter and height of each tree had been measured each 5 years. Tree-volume increment and total plot-volume increment were calculated from tree diameter and height and a local volume equation. The sum of squares of (tree percent of plot-volume increment - estimated tree percent)^2 was then minimized by iteration with different powers of diameter and height until the best combination was found. Trees on the levels-of-growing-stock plots were used to fit the tree-increment proportion equation. Trees ranged in size from 3 inches in diameter 20-feet tall to 13-inch 60 footers.

Height of the tallest tree per 1/5 acre is obtained from curves for estimating site index or height growth. If the stand is 20 years old or less, height-growth curves are used. If the stand is older, site-index estimating curves are used. These curves have a 100-year index age. They are more fully described in Dahms (1975).

To go from height of the tallest tree or trees to height of lesser trees, height is expressed as a percentage of the tallest at the start. This percentage is used through the years in the simulation process.

The assumption that relative height of trees remains the same is not entirely true (Dahms 1963); however, future height is almost certainly more closely related to past height than to diameter.

Mortality

Two unlike sources of mortality data were available for central Oregon lodgepole pine. The first was two levels-of-growing-stock studies, one at Twin Lakes (see Dahms 1971b) that was 22 years old at the time the study was installed and the other at Snow Creek (see Dahms 1973), 47 years old. For both studies, a 15-year record of growth and mortality was available. The stands are considered healthy, but some rust cankers were present in both. Thinning discriminated heavily against cankered trees, however.

The second source of mortality data was a thinning study of three plots installed in a 55-year-old stand at the Pringle Falls Experimental Forest. Two of the plots were thinned, one heavily and the other moderately; the third was left unthinned. The stand was so heavily infected with rust cankers caused by *Peridermium harknessii* and *P. stalactiforme* that Beeman[5] reported 67 percent of the reserve trees on the thinned plots were infected.

Mortality from the levels-of-growing-stock studies represents what might be expected in a healthy managed stand. The Pringle Falls results are an example of the kind of mortality that can occur in a stand heavily infected with rust cankers.

[5] Beeman's unpublished report is quoted in Dahms (1971a). The original report was burned in the 1974 Silviculture Laboratory fire.

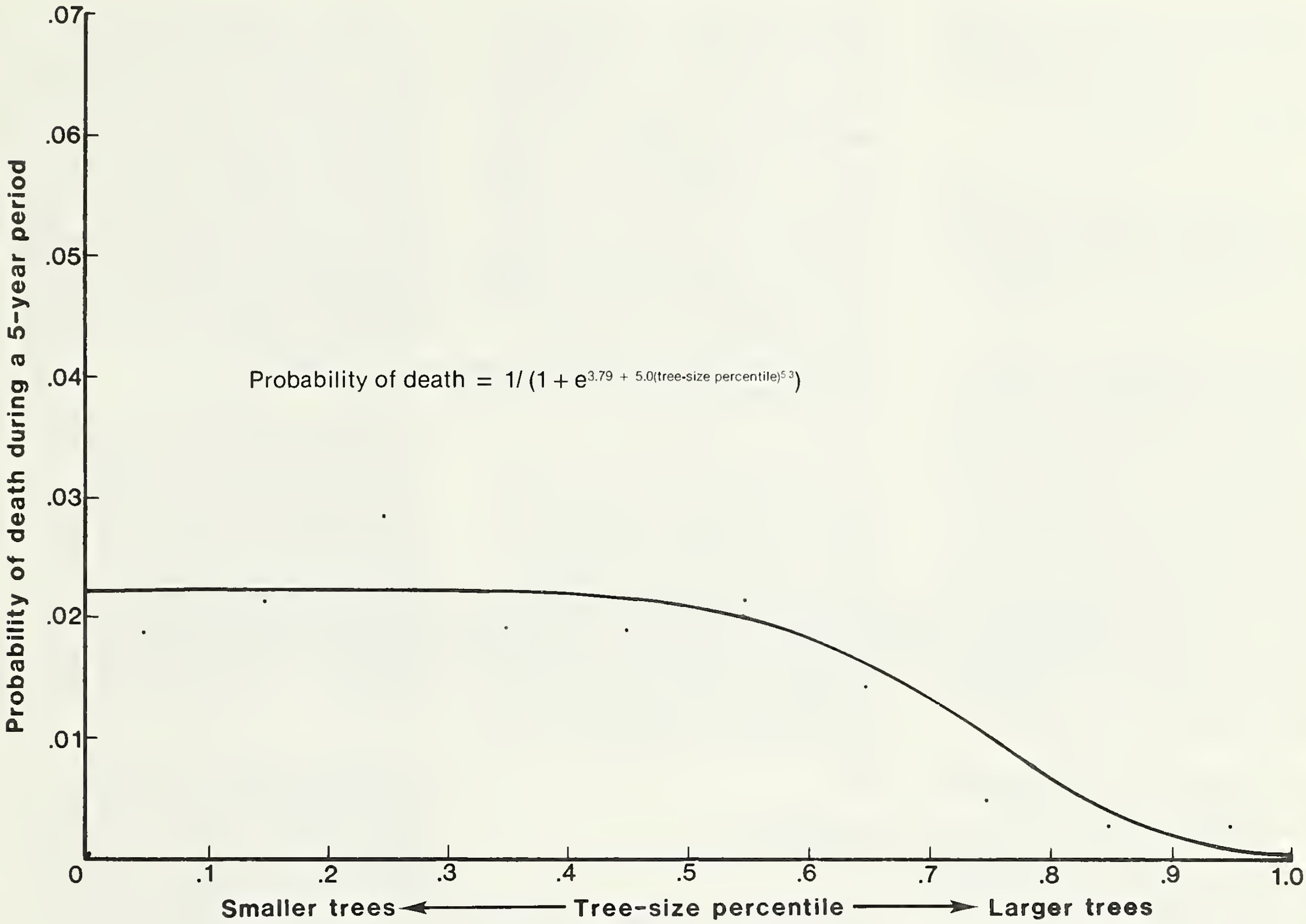


Figure 6. — Probability of a tree dying during a 5-year period as related to tree-size percentile at Snow Creek and Twin Lakes — the managed-stand option.

To express mortality as a probability of death in an equation for any given tree to use in a computer simulation model, we borrowed some ideas from Hamilton (1974) and Hamilton and Edwards (1976). The equation form chosen was

Probability of death

$$= 1/(1 + e^{(A + B\,(\text{tree-size percentile})^{N})}).$$

To fit this equation, trees at the start of the 5-year period in question were ordered by size from smallest to largest. They were then divided into 10 groups as nearly equal as possible. The number of trees that died during the period was determined for each tree-size percentile group. An average probability of death for any given tree in any given tree-size percentile group could then be calculated.

The process for tree-size percentile grouping started out plot by plot for each period for the levels-of-growing-stock study data, but all were eventually added together for all periods and for all plots at both locations. The graph of figure 6 shows the relation of probability of death to tree-size percentile. The equation

Probability of death

$$= 1/(1 + e^{(3.79 + 5.0\,(\text{tree-size percentile})^{5.3})})$$

accounted for 89 percent of the variation in probability of death. A chi-square test also confirmed the significance of the relation of tree-size percentile to probability of death, with the smaller trees more likely to die. This is the mortality obtained if the "managed stand" mortality option is selected.

An attempt was made to fit the same kind of equation to the Pringle Falls data, but no relation to tree size was found. Consequently, one average probability of death was used regardless of tree size.

To convert the 32-year mortality record to a probability of death for a given tree for a 1-year period, the compound-interest formula was used as described by Hamilton and Edwards (1976).

Probability of death for a given tree during a 1-year period over the 32 years averaged .01414 for the heavily thinned plot, .012703 for the moderately thinned one, and .01958 for the unthinned area. Average probability for all plots during a 1-year period was .01675, a figure heavily weighted in favor of the unthinned plot because it had many more trees on it. The average for all plots is the probability called when "Pringle Falls" mortality is selected. "Pringle Falls" mortality is about 4 times that of the "managed-stand" option and 2½ times the north Idaho or natural-stand option.

A combination of the "managed-stand" mortality for young stands and "natural-stand" mortality for older ones, provides what seems like a reasonable estimate of mortality for many stands. Such an estimate is available if the "combined-mortality" estimate is called. "Managed-stand" mortality is used to age 60; thereafter, "natural-stand" mortality is substituted.

Thinning

The probability that a given tree will be cut has been treated very much like the probability that a given tree will die. Because thinning was from below, smaller trees were much more likely to be cut than larger ones.

Equations expressing probability of cut as a function of tree-size percentile were fitted to individual-plot data from the Twin Lakes and Snow Creek levels-of-growing-stock studies previously described. The equation shown as figure 7 indicates about half of the trees were cut. All of the smallest trees were removed by thinning. In the zone between the .3 to .7 tree-size percentile, probability of cutting a tree drops rapidly as size increases until the probability of trees larger than the .7 percentile being removed is very small. This equation fit the data well, with tree-size percentile accounting for 97 percent of the variation in probability of cut.

To fit equations like the one shown in figure 7 to cut and leave data for a given plot, all trees are arrayed in order of diameter from the smallest to the largest. Trees are then divided into about 10 groups of as nearly equal size as possible. Number of groups can be adjusted somewhat to aid in keeping all groups the same size. For each group, a probability of cut is calculated by dividing number cut by total number of trees in the group. An equation of the form

$$\text{Probability of cut} = e^{-K(\text{tree-size percentile})N}$$

is fit. An iteration approach is required to obtain the best fitting K and N coefficients. The equation form is well suited to dealing with probability because it can only assume values between 0 and 1.

To make the probability of cut equations useful in the simulation model, a family of curves like that shown in figure 8 is needed. Data from thinnings at Twin Lakes and Snow Creek levels-of-growing-stock studies provided the basis for the curves of figure 8. Equations like that shown as figure 7 were fitted to plots covering a wide range of cut intensities. Equations expressing the coefficients K and N as functions of percent cut provide the basis for the required curve family that permits the simulator user to obtain any percent of cut desired.

Percent of cut specified is not always exactly achieved, partly because the choice of trees to be cut contains a random element. This effect can be averaged out by making several runs with a different random number start each time. Failure of equations to fit perfectly also causes some discrepancy between percent cut specified and result achieved by the simulator. This discrepancy is small, however.

Tree size combined with vigor and spacing were the main criteria for selecting trees to be cut at Twin Lakes. The family of curves shown as figure 8 depicts primarily the size-spacing effect. Thinning in stands where trees were infected with rust cankers or other diseases tends to show less correlation between relative tree size and probability of cutting.

A probability-of-cut equation can easily be developed for specific stands and marking rules by marking cut and leave trees with paper tags. Access to some kind of computer is needed to fit the equations.

Tree-Volume Equations

Total cubic-foot volume per tree inside bark including stump and tip was the starting point for all volume estimates. Board-foot volumes and merchantable cubic-foot volumes were obtained from total cubic-foot volume.

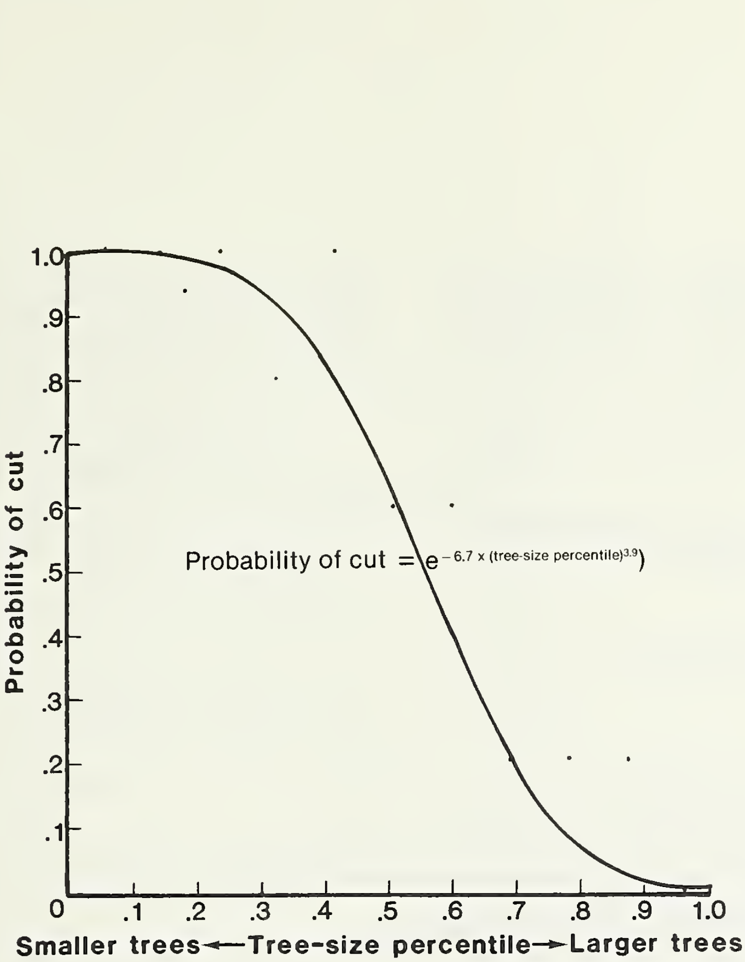


Figure 7. — Probability of a tree being cut as related to tree-size percentile. Twin Lakes plot number 1, 1964 thinning.

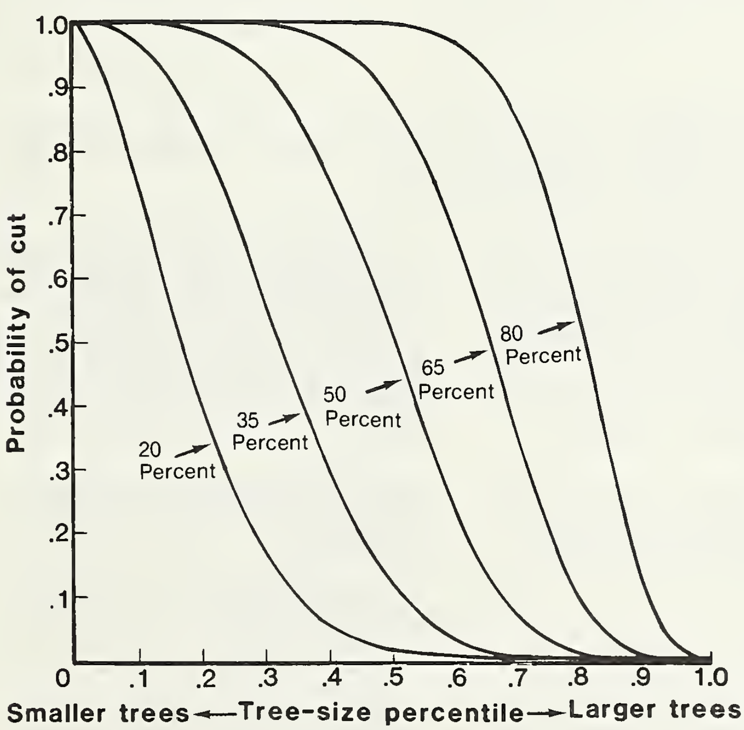


Figure 8. — Family of curves of probability of cutting a tree over tree-size percentile. Each curve results in a different percent of trees cut.

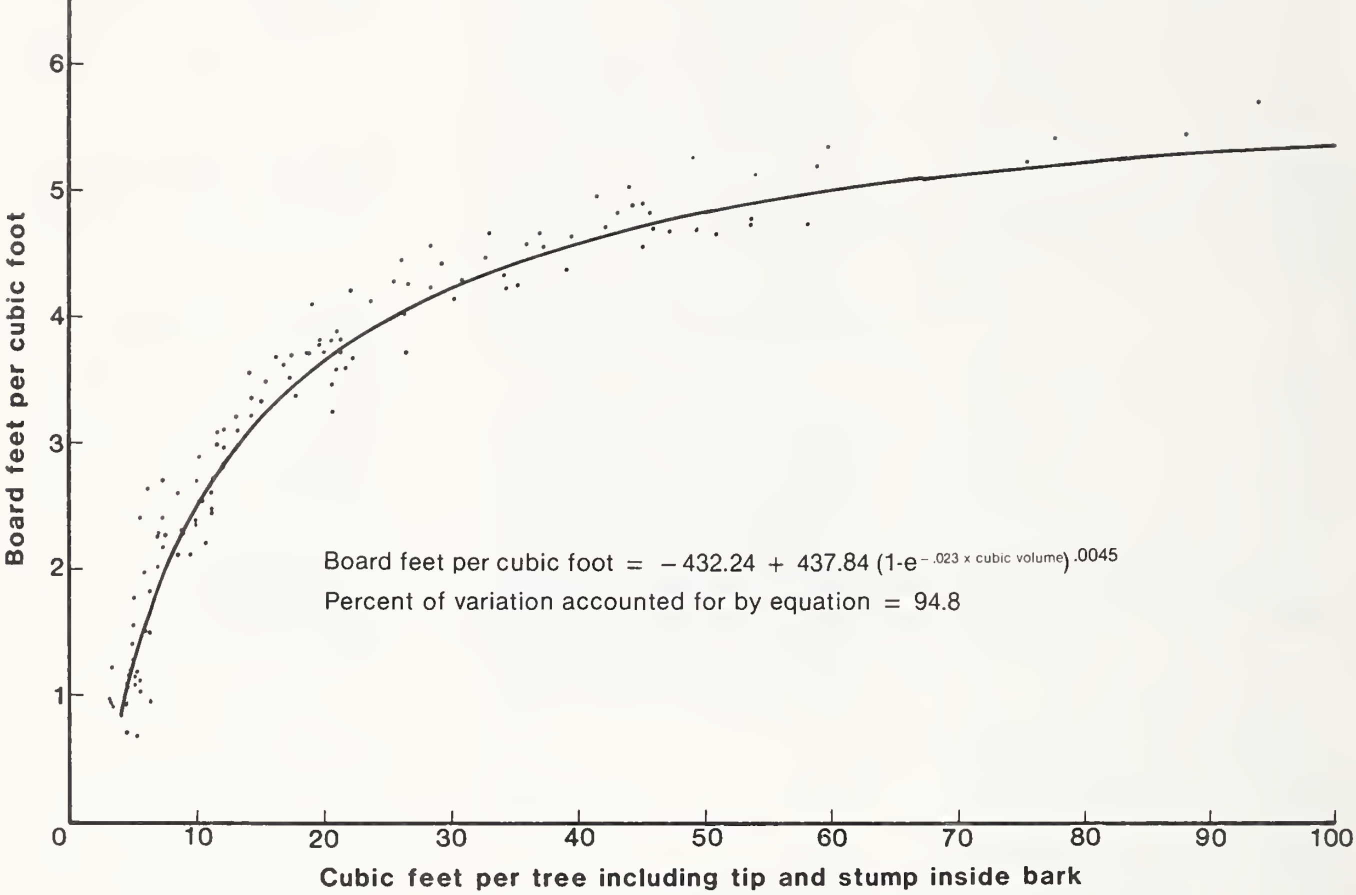


Figure 9. — Scribner board feet per cubic foot to a 5.0-inch top as a function of cubic-foot volume per tree.

Cylindrical form class volume equations of the type developed by Bruce and DeMars (1974) were used to estimate total stem volume of individual trees. The equation,

$$\text{Form} = .2539 - .5960/D + .0239\ (H/D) + 4.8422/H + 30.4688/H^2,$$

was fitted to data for 194 trees felled and cut up as a part of the central Oregon gross-yield study (Dahms 1964). Volume was calculated from the equation

$$\text{Volume} = F \times D^2 \times .005454154 \times H$$

where F = cylindrical form factor, D = d.b.h. outside bark in inches, H= total tree height in feet, and volume = total cubic stem volume inside bark including stump and tip.

To help those unfamiliar with this equation to visualize it, the expression $D^2 \times .005454154 \times H$ is the volume of a cylinder, in cubic feet, with length equal to height of the tree and diameter equal to tree diameter breast high outside bark. F is the portion of this cylinder occupied by wood inside bark.

Board-foot estimates were obtained from board feet per cubic foot ratios. The equation

$$\text{Scribner board feet to a 5.0-inch top} = -432.24 + 437.84\ (1 - e^{-.023 \times \text{cubic volume}})^{.0045},$$

together with the values used to derive the equation, are shown graphically as figure 9. The equation fits the data points well, accounting for 94.8 percent of the variation in board feet per cubic foot.

Eight equations of this general form were fit, one for each log rule to a 5.0-, 6.0-, 7.0-, and 8.0-inch top. For the International log rule, the four equations for board feet per cubic foot were:

To a 5.0-inch top = $-3.35 + 9.21 (1 - e^{-.056 \text{ cubic volume}})^{.3}$.

To a 6.0-inch top = $-76.25 + 82.025 (1 - e^{-.055 \text{ cubic volume}})^{.035}$.

To a 7.0-inch top = $-9.02 + 14.82 (1 - e^{-.06 \text{ cubic volume}})^{.31}$.

To an 8.0-inch top = $-1.26 + 7.135 (1 - e^{-.066 \text{ cubic volume}})^{1.3}$.

For the Scribner log rule, the equations were:

To a 5.0-inch top = $-432.24 + 437.84 (1 - e^{-.023 \text{ cubic volume}})^{.0045}$.

To a 6.0-inch top = $-448.85 + 454.42 (1 - e^{-.025 \text{ cubic volume}})^{.0046}$.

To a 7.0-inch top = $-55.05 + 60.49 (1 - e^{-.035 \text{ cubic volume}})^{.049}$.

To an 8.0-inch top = $-494.21 + 499.69 (1 - e^{-.0345 \text{ cubic volume}})^{.007}$.

Percentage of variation in board feet per cubic foot accounted for ranges from 88.0 for the International board feet to a 6.0-inch top to 94.9 percent for the Scribner board-foot equation to a 6.0-inch top. Board feet per cubic foot is strongly correlated with tree size, and the equations describe the relationship well.

Any given tree size always has more International board feet per cubic foot than Scribner. This is more pronounced for smaller trees than larger. Also, the particular merchantable top used has more effect on International board-foot volume than Scribner (fig. 10, table 2). Because tree size is indicated in terms of average stand diameter in table 3 instead of total cubic volume as in figure 9, studying both the table and the figure helps produce a better mental image of the relationships.

Merchantable cubic volumes to a 3.0-, 4.0-, or 5.0-inch top were derived from total cubic volume. The three equations for merchantable cubic volume were:

To a 3.0-inch top in cubic feet = $.49 + 422.33 (1 - e^{-.003 \times \text{total cubic volume}})^{1.097}$.

To a 4.0-inch top in cubic feet = $-.29 + 598.18 (1 - e^{-.00198 \times \text{total cubic volume}})^{1.059}$.

To a 5.0-inch top in cubic feet = $-1.68 + 11948.3 (1 - e^{-.00008 \times \text{total cubic volume}})^{.992}$.

These equations all accounted for 99.9 percent of the variation in merchantable cubic volume. Despite the very high R-square values, the equation expressing merchantable cubic volume to a 3.0-inch top shows slightly more merchantable volume than total for trees with less than 3 cubic feet. Because the error is small and few such trees are dealt with, this problem is not serious.

The total cubic-foot volume used was total stem volume inside bark including stump and tip. Board-foot and merchantable cubic volume were both for that portion of the stem above the stump, as cut, to the specified top diameter. Stumps ranged from 0.1 to 0.9 foot in height and averaged .43 foot. Because higher stumps tended to be left on larger trees, the average stump for trees of board-foot size was probably slightly higher than .43 foot.

Testing the Simulation Model

Three approaches to testing the simulation model were taken:

1. A comparison of predicted and actual performance on three Pringle Falls plots over a 32-year period and from plots on two levels-of-growing-stock studies over a shorter period of time.
2. A comparison of gross and net yields with gross yield representing a cumulative total of gross increment.
3. A comparison of predicted and actual diameter distribution, total net volume, and average diameter for some older gross-increment plots.

If enough plots with long periods of measured growth were available, only the first approach would have been used, but such plots do not exist.

Comparison With Permanent Sample Plots

Two sets of simulation runs were made to compare actual performance on the Pringle Falls plots with that estimated by the simulator. Simulation started with the stand as it existed at age 55 years, after thinning had taken place. In one trial, a mortality calculated for each plot was used in the simulator, but in the other, "combined mortality" was used.

Estimated net-volume increment was substantially below actual when mortality estimates developed for each plot were used (table 3). Estimates were 65, 56, and 62 percent of actual net increment for plots 11, 12, and 13, respectively. Average diameter too was underestimated.

Gross-volume increment also was underestimated, but because mortality was such a large part of it, the underestimate was not so large in terms of percent. Estimated gross-volume increment amounted to 76, 71, and 83 percent of actual gross increment for plots 11, 12, and 13, respectively.

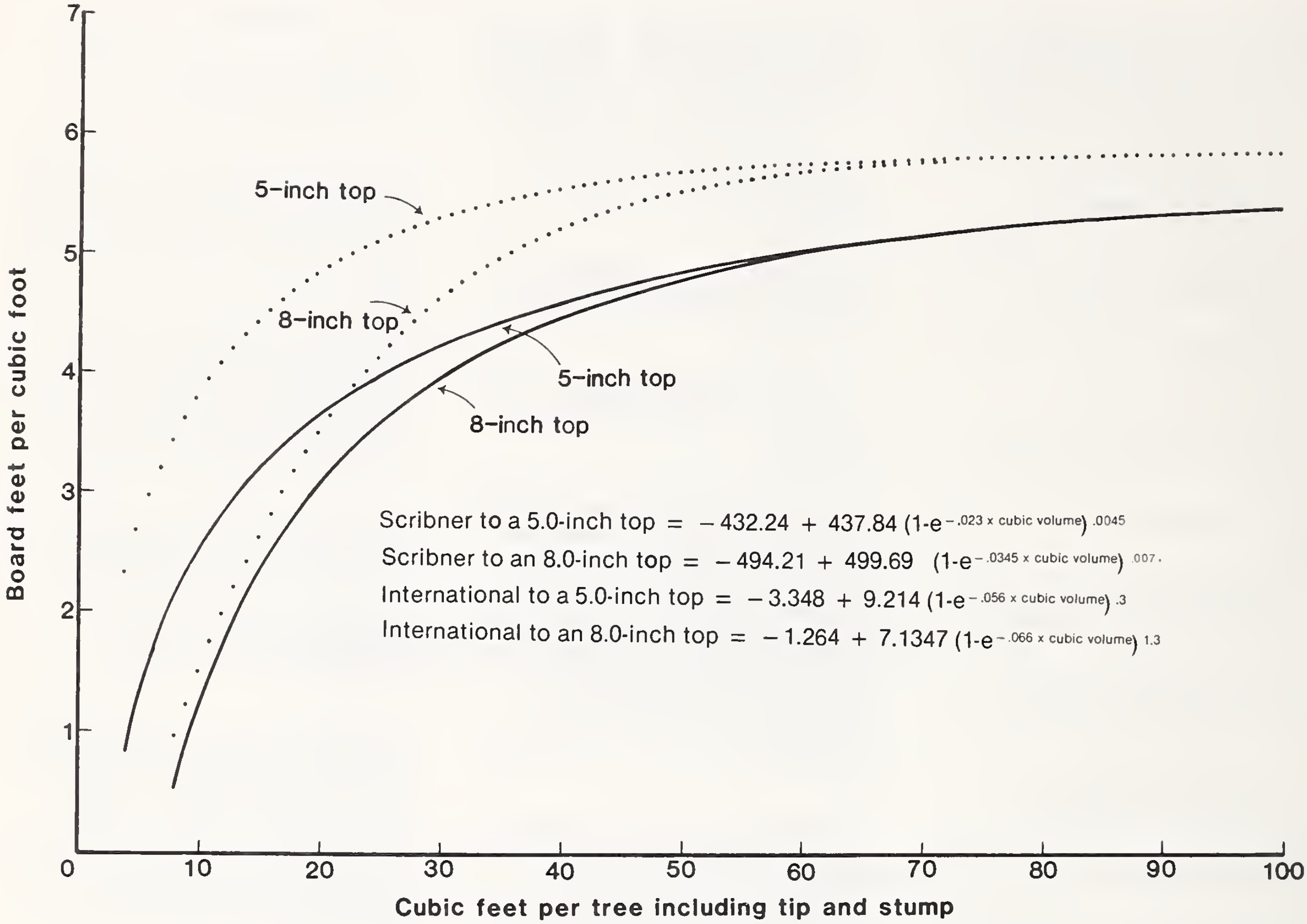


Figure 10. — Board feet per cubic foot International (dotted) and Scribner (solid), as a function of cubic feet per tree. Both rules to 5.0- and 8.0-inch tops.

Table 2 — Comparison between Scribner and International board-foot volumes to 5.0- and 8.0-inch tops at stand average diameters of 11.6 and 15.8 inches[1]

Stand average diameters	Scribner volume		International volume	
	5.0-inch top	8.0-inch top	5.0-inch top	8.0-inch top
Inches	*Board feet*			
11.6	10,787	9,099	14,167	10,539
15.8	24,889	24,115	28,745	27,232

[1] The stand had 166 trees at age 63 years when the average diameter was 11.6 inches, but mortality had reduced the number to 111 trees at 118 years when the average diameter was 15.8 inches.

Breaking the total 32-year growth period into six 5-year measurement periods and one 7-year period provides more insight into possible reasons for the greater actual than estimated wood production (table 4). Gross-volume increment increased substantially during the third and fourth measurement periods, exceeding that during the first measurement period despite increasing age, especially on plot 12.

The trend of volume increment with age on the unthinned plot is more in line with the usual expectation, a fairly steady decrease with increasing age. Some increase occurred during the third and fourth periods, but the rise was not nearly as great as that on the thinned plots.

Estimated net-volume increment came very close to actual for the two thinned plots when combined mortality was used (table 5). Estimated far exceeded actual increment for the unthinned plot, however.

Actual mortality substantially exceeded that estimated by the combined mortality equation. On the unthinned plot, only 338 of the original 640 trees per acre were alive at the end of the 32-year period (table 5). By the combined mortality equation, 527 trees were estimated to be alive.

Actual mortality greatly exceeded estimated. The Pringle Falls plots are located in a pocket where a high percentage of trees were infected with rust cankers. No equation designed to estimate mortality over a broad area could be expected to fit such a small area. If a mortality equation were based on individual tree attributes including rust cankers, however, it probably could.

Table 3 — Comparison of actual and estimated diameter distribution, average diameter, and net-volume increment (all values per acre) for Pringle Falls lodgepole pine plots 11, 12, and 13 after 32 years of growth (estimates using Pringle Falls mortality)

Item	Plot 11		Plot 12		Plot 13	
	Actual	Estimate	Actual	Estimate	Actual	Estimate
			Number of trees			
Diameter class, inches:						
4.5 and less	0	2	0	0	60	94
4.6-6.5	6	9	4	27	96	96
6.6-8.5	10	22	56	72	70	72
8.6-10.5	24	27	68	43	80	40
10.6-12.5	38	18	38	16	26	20
12.6-14.5	18	12	26	16	6	10
14.6-16.5	6	4	4	6	0	3
16.6 and up	2	6	2	8	0	4
Total	104	100	198	188	338	339
			Inches			
Average diameter	11.0	10.1	10.0	9.2	7.1	6.9
			Cubic feet			
Annual net-volume increment	35.8	23.4	50.6	28.4	21.3	13.4

Table 4 — Gross periodic cubic increment[1] per acre, Pringle Falls plots 11, 12, and 13

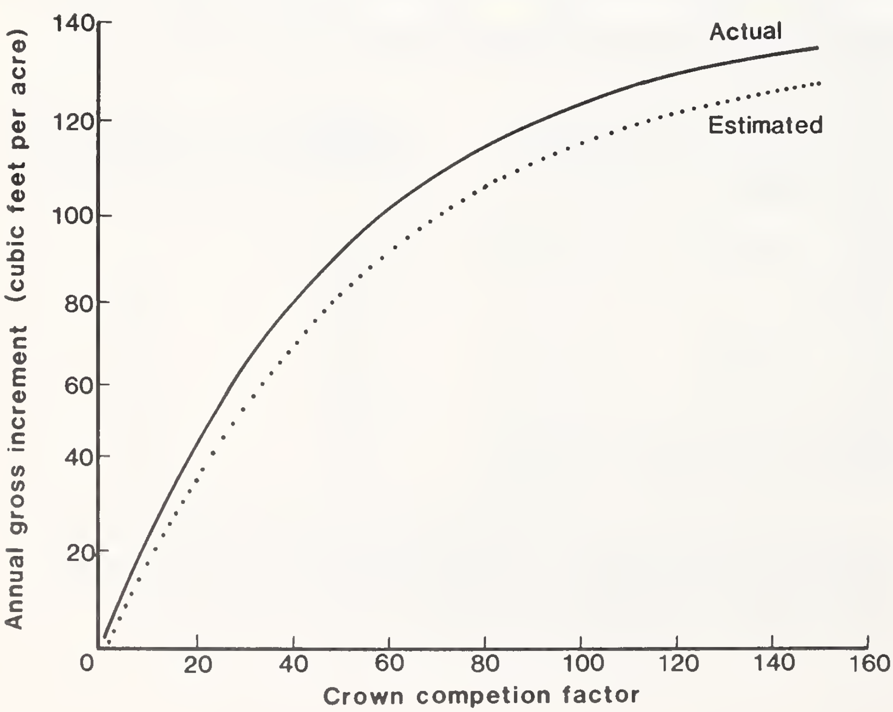
Period	Plot 11 16 × 16 feet	Plot 12 Thinned, 12 × 12 feet	Plot 13 Unthinned
Years		*Cubic feet*	
1935-39	59.6	71.2	83.5
1940-46[2]	58.3	67.8	64.2
1947-51	61.5	86.7	74.8
1952-56	67.5	100.8	79.0
1957-61	61.8	67.3	64.9
1962-66	43.3	49.6	40.5
1935-66	58.6	73.5	67.6

[1] Increment for the full 32-year period does not agree exactly with that shown in table 3 because the volume equation from the simulation model was used for the table 3 figures. The volumes shown here were taken directly from table 4 of an earlier publication (Dahms 1971a). In the earlier instance, a different equation was used to express tree volume.

[2] This growth period was lengthened because research ceased during World War II.

Table 5 — Comparison of actual and estimated diameter distribution, average diameter, and net-volume increment (all values per acre) for Pringle Falls lodgepole pine plots 11, 12, and 13 after 32 years of growth (estimates using combined mortality)

Item	Plot 11		Plot 12		Plot 13	
	Actual	Estimate	Actual	Estimate	Actual	Estimate
			Number of trees			
Diameter class, inches:						
4.5 and less	0	2	0	0	60	136
4.6-6.5	6	12	4	41	96	152
6.6-8.5	10	32	56	84	70	123
8.6-10.5	24	41	68	63	80	63
10.6-12.5	38	25	38	18	26	32
12.6-14.5	18	17	26	2	6	10
14.6-16.5	6	4	4	8	0	6
16.6 and up	2	5	2	10	0	5
Total	104	138	198	236	338	527
			Inches			
Average diameter	11.0	9.9	10.0	8.9	7.1	6.6
			Cubic feet			
Annual net-volume increment	35.8	42.8	50.6	47.1	21.3	51.4



The good correspondence between actual net increment and what was estimated, including the combined-mortality estimate, resulted from a lucky combination of underestimated gross-volume increment and under-estimated mortality (table 5).

To sum up, the gross-increment equation underestimated gross increment on all of the plots, but particularly on the thinned ones. The amount of underestimate for the unthinned plot is certainly within the range of variation exhibited by the temporary plots used to develop the gross-increment equation. An extra response from thinning probably accounts for some of the difference between actual performance and estimated in the thinned plots, however.

The Twin Lakes and Snow Creek levels-of-growing-stock plots also provide a basis for testing performance of the gross-increment equation. Because only the shape of the curve of volume increment over stand density used in the simulator was derived from levels-of-growing-stock studies, comparing total actual production with that estimated by the simulation model seems reasonable.

Actual performance at Twin Lakes during the third 5-year growth period corresponds closely with that estimated by the simulator (fig. 11). Estimated increment amounted to 94.4 percent of actual. The curve for the fourth period fell almost exactly on top of the third-period curve, but because of increasing stand age the estimated increment would be slightly less. During the first two periods, volume increment similarly fell close to that predicted with a slight drop from the first period to the second.

Figure 11. — Actual versus estimated gross cubic-volume increment at Twin Lakes levels-of-growing-stock study.

Data from the Snow Creek levels-of-growing-stock study during the third 5-year growth period showed estimated gross cubic-volume increment to be 72 percent of actual. During the first period, the very irregular curve of volume increment over stand density came close to touching the estimated curve at the highest point but was generally well below the estimated curve (Dahms 1973). Data for the second period are not yet available. I suspect that thinning in this somewhat overdense 47-year-old stand produced an extra response that temporarily pushed actual performance above that estimated by the simulation model during the third period, just as apparently happened in the Pringle Falls plots. Data from this study during several more growth periods might reveal some important trends of volume increment in thinned stands.

Gross cubic-volume increment at Snow Creek started out very low during the first 5-year period after thinning (Dahms 1973). By the third period, however, increment had surged substantially ahead of estimated. The surge may well be a result of thinning an older stand (47 years); the younger stand at Twin Lakes (34 years) did not produce such a surge. Results from thinned stands such as those just described suggest that the levels-of-growing-stock studies are well worth maintaining.

Comparison of Gross and Net Yields

Comparison of gross and net yields tests the reasonableness of the gross-yield equation. Gross yield represents a cumulative total obtained by solving the gross-increment equation starting at age 10, then age 11 and adding it to the age 10 result, age 12, and adding it to the previous total, and so on to the desired age.

Net yield represents the live volume actually standing at the time the 94 gross-yield plots were examined. No attempt was made to eliminate defect from the standing volume.

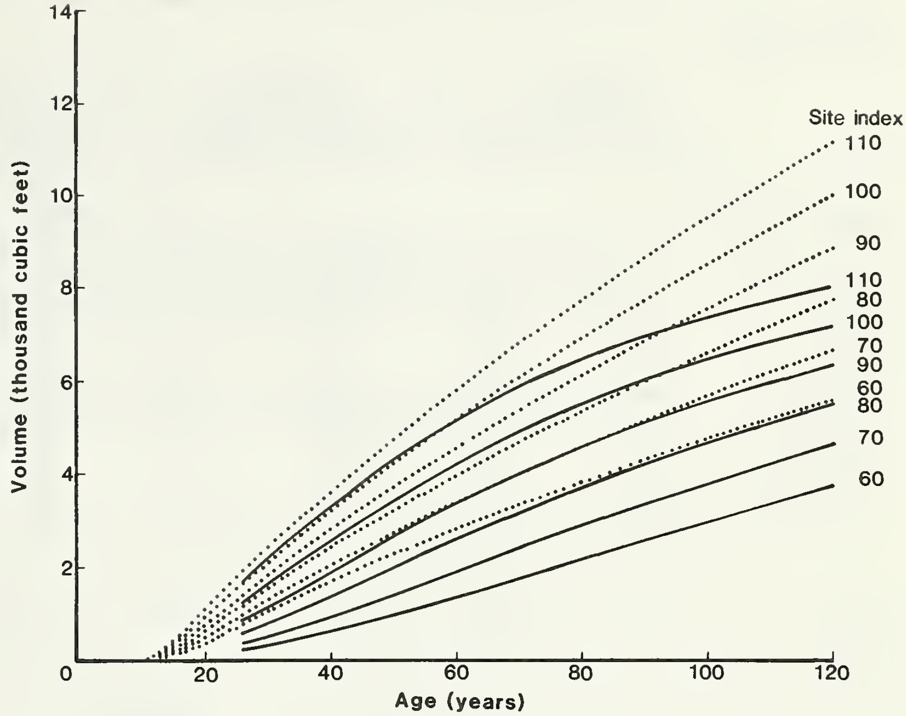


Figure 12. — A comparison of gross and net yield by age and site index at C.C.F. 175.

Net yield is expressed in equation forms as a function of age, stand density (C.C.F.), and site index. Like gross yield, it represents total cubic volume of all trees 2.6 inches in diameter and larger, including tips and stumps.

Figure 12 shows that gross yield always exceeds net; that is as it should be, because stands as old as 25 or 30 years almost certainly will have suffered some mortality or they will have been understocked during an earlier part of their lives or, usually, a little of each. At age 120 years, net yield represents from 67.3 percent of gross at site index 60 to 71.8 percent at site index 110 with a fairly steady progression of increasing percentage with increasing site index.

A comparison of gross- and net-yield ratios for other species helps put these for lodgepole pine into perspective. For ponderosa pine, Meyer (1938) reported mortality and net yields such that net yield constituted 69, 74, and 76 percent of gross at site indices 60, 80, and 100 at age 120 years. Similarly, for Douglas-fir, Staebler (1955) reported net yields represented from 71 to 75 percent of gross yield at age 120 years. The percentages for lodgepole pine thus look reasonable.

Table 6 — Actual and estimated diameter distribution, average diameter, and net cubic volume per acre on 4 lodgepole pine gross-yield plots

Item	Plot 66, site index 73		Plot 51, site index 100		Plot 68, site index 93		Plot 57, site index 83	
	Actual	Estimate	Actual	Estimate	Actual	Estimate	Actual	Estimate
				Number of trees				
Diameter class, inches:								
4.5 and less	10	3	25	4	75	8	0	4
4.6-6.5	0	5	5	7	20	39	0	5
6.6-8.5	10	21	15	35	15	59	25	23
8.6-10.5	25	34	10	36	40	84	45	41
10.6-12.5	60	44	75	46	65	68	75	49
12.6-14.5	30	38	45	44	80	48	35	56
14.6-16.5	25	22	25	27	10	8	25	24
16.6 and up	10	11	5	7	20	4	5	20
Total	170	178	205	206	325	318	210	222
				Inches				
Average diameter	11.9	11.8	11.0	11.3	9.7	9.9	11.6	11.9
				Cubic feet				
Net volume	4,317	4,075	5.685	5,722	7,522	6,247	5,393	5,592

Actual Versus Estimated Diameter-Class Distributions

Estimated diameter distribution has matched actual distribution quite well over a long simulation period (table 6). Plots 51 and 68 had more very small trees than were estimated. Plot 57, however, had no very small trees, although the simulation model estimated some. A comparison of average diameter and net volume also showed close correspondence.

The actual figures were obtained from the existing stand on some of the older gross-yield plots. The youngest stand, sampled by plot 51, was 100 years old and the oldest, sampled by plot 68, was 122 years old.

We have no way of knowing what these stands looked like at age 20 or 25 years. The estimated figures were obtained by simulating growth of a 19-year-old stand at the site index of the older plot. Age of the young stand was adjusted to match actual height and the imposed site index. Plots in the young stand with spacings of 6, 9, 12, 15, and 18 feet were available (see footnote 3). A plot with a spacing was chosen that would end up with a number of trees similar to the older plot where trees had been measured.

A better comparison could be made if the number and size of trees at the beginning were known. To get the kind of correspondence achieved here, the gross-increment equation had to provide good estimates, the height-growth mechanism had to work well, and increment allocation to individual trees had to be close to what actually occurred.

Dahms, Walter G. A growth simulation model for lodgepole pine in central Oregon. Res. Pap. PNW-302. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1983. 22 p.

A growth-simulation model for central Oregon lodgepole pine *(Pinus contorta* Dougl.) has been constructed by combining data from temporary and permanent sample plots. The model is similar to a conventional yield table with the added capacity for dealing with the stand-density variable. The simulator runs on a desk-top computer.

Keywords: Lodgepole pine (*Pinus contorta* Dougl.), yield table, variable stand density, growth simulation, gross increment, mortality, net increment, central Oregon.

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